LOW X MEETING:

HELSINKI, FINLAND, August 29 - September 1 2007

MHV rule, (Super)Symmetries and 'Diffractive Higgs'

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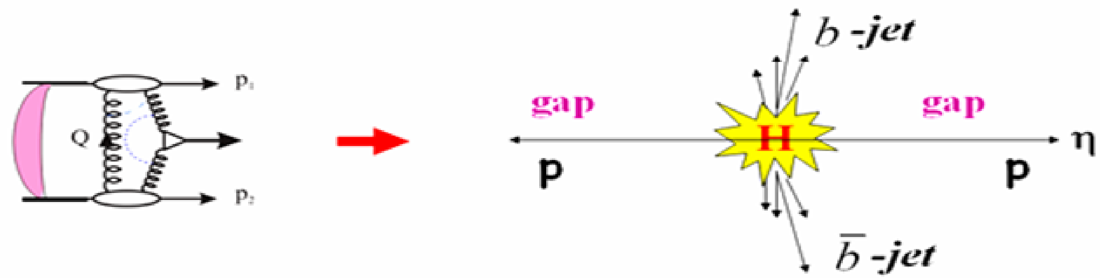
Main aims
- MHV rules and SUSY at the service of 'diffractive Higgs'
- major QCD backgrounds to H→bb production at the LHC in the forward proton mode

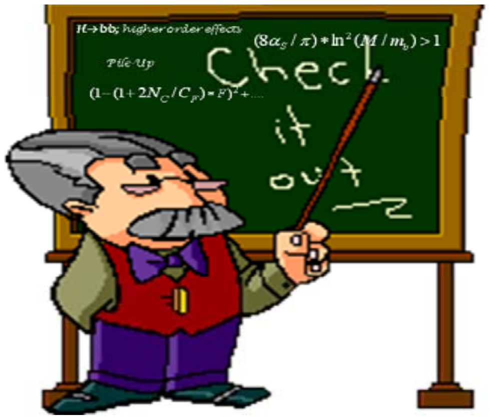
(based on works with M.G. Ryskin, A.D. Martin and W.J. Stirling)



Higgs sector study- one of the central targets of FP420 physics menu
(Mike, Brian, Ken, Andy, Marek, Vojtech, ADR, Christophe)

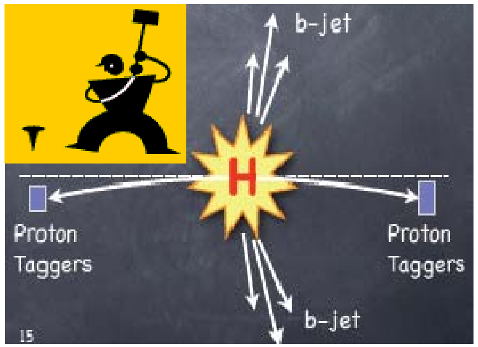
For theoretical audience

MHV rules, Super (symmetry) and
'Diffractive Higgs' at the LHC



For experimental audience

Non- Pile-Up Backgrounds to
Diffractive Higgs Production
at the LHC



Forward Proton Mode- Main Advantages: (Brian, Marek, Andy)

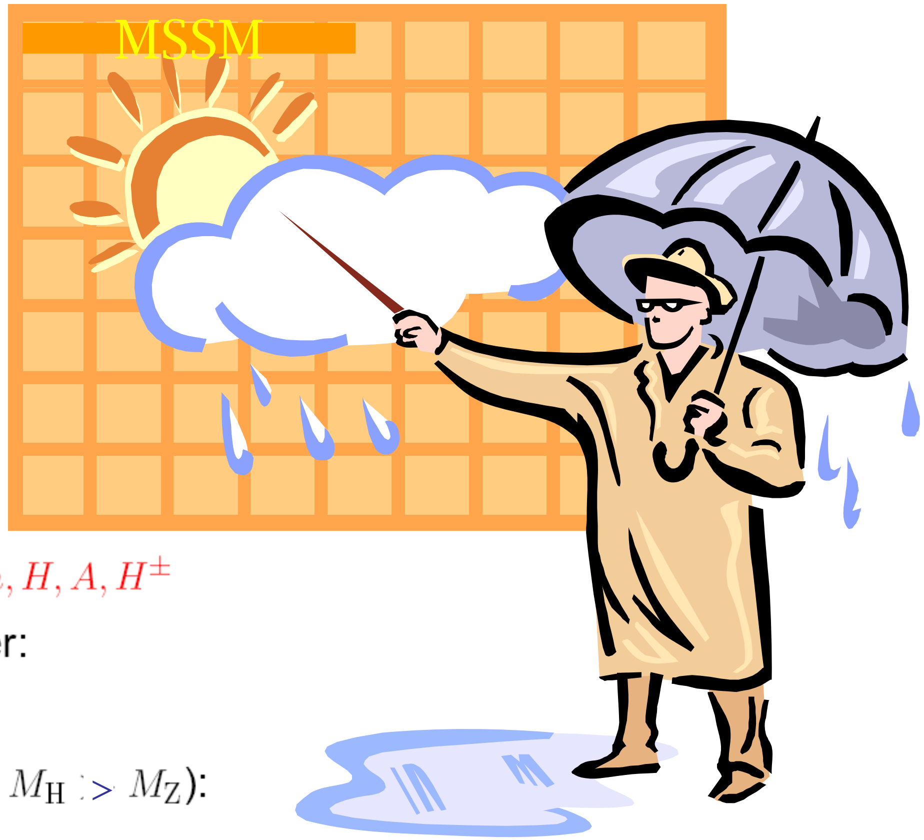
- Measurement of the Higgs mass via the missing mass technique (irrespectively of the decay channel)
- Direct H →bb mode opens up (Hbb Yukawa coupling);
  unique signature for the MSSM Higgs sector.
- Quantum number/CP filter/analyzer
- Cleanness of the events in the central detectors.

without 'clever hardware':

for H(SM)→bb at 60fb-1 only
a handful of events due to
severe exp. cuts and low efficiencies,
though **S/B~1**

but **H->WW** mode at M>135 GeV

situation in the MSSM is **very different**
from the SM (HKRSTW-07)



- Higgs sector of the MSSM: physical states $h, H, A, H^{\pm}$

  Described by two parameters at lowest order:
  $M_{\mathrm{A}}, \tan\beta \equiv v_2/v_1$

- Search for heavy MSSM Higgs bosons ($M_{\mathrm{A}}, M_{\mathrm{H}} \gg M_{\mathrm{Z}}$):
  Decouple from gauge bosons
  $\Rightarrow$ no HVV coupling
  $\Rightarrow$ no Higgs production in weak boson fusion
  $\Rightarrow$ no decay $H \to ZZ \to 4\mu$

  Large enhancement of coupling to $b\bar{b}$ (and $\tau^+\tau^-$) in region of high $\tan\beta$

(Marek's, Andy's talks)

4^{th} generation→factor of 5 rise in bb rate

Conventionally due to overwhelming QCD backgrounds, the direct measurement of Hbb is hopeless

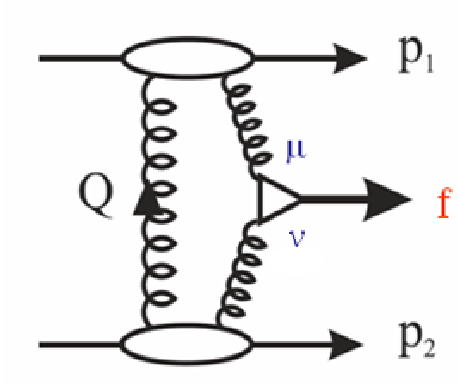
The backgrounds to the diffractive H bb mode are manageable but should be studied very thoroughly ! MHV technique is very CEDP friendly.

for Higgs searches in the forward proton mode QCD backgrounds are suppressed by Jz=0 selection rule and by colour, spin and mass resolution ($\Delta M/M$) –factors. (KMR-2000)

There must be a god

Do not need *many* events to establish cleanly that the Higgs is a scalar and to measure the mass

The origin of Jz=0 selection rule



$$M_{\mu\nu}(gg^{PP}) \sim (p_{t,1} - Q_t)_\mu (p_{t,2} + Q_t)_\nu$$

after $(\bar{Q}_t)$ angular integration at $p_{t,i} = 0$ → $-\delta^{(2)}_{\mu\nu} Q_t^2 / 2$

(J. Pumplin 1995)

in terms of helicity amplitudes . $1/2\{(++;f) + (--;f)\}$ → Jz=0, P-even state

at non-zero $p_{t,i}$ - an admixture of Jz=2 → $\frac{(2p_{1,t}p_{2,t})^2}{Q_t^4}$

some regions of the MSSM parameter space are especially *proton tagging friendly*
(at large tan β and M ≤ 250 , S/B ≥ 20)

KKMR-04

S. Heinemeyer et al 0.7083052[hep-ph]   B. Cox, F.Loebinger, A.Pilkington-07

Myths

For the $b\bar{b}$ channel bgds are well known and incorporated in the MCs:

Exclusive LO - $b\bar{b}$ production (mass-suppressed) + *gg* misident+ soft & hard PP collisions.

Reality

The complete background calculations are still in progress
(uncomfortably & unusually large high-order QCD and b-quark mass effects).

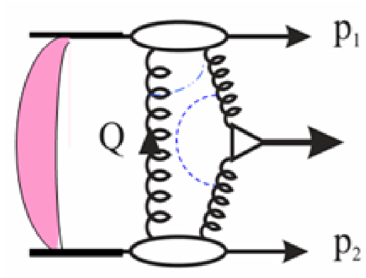
About a dozen various sources (studied by Durham group)

On top of MC studies
(Andy, Marek et al.)

❶ admixture of |Jz|=2 production.
❷ NLO radiative contributions (hard blob and screened gluons)

❸ NNLO one-loop box diagram (mass- unsuppressed, cut-non-reconstructible)'
❹ 'Central inelastic' backgrounds
❺ b-quark mass effects in dijet events – *still incomplete*
potentially, the largest source of theoretical uncertainties!

KMR technology (implemented in ExHume MC)



$$\sigma_{pp}(M^2,\ldots) = L_{eff}(M^2, y) * \sigma_{hard}(M^2,\ldots)$$

$$\frac{\partial^2 L_{eff}}{\partial y \partial M^2} M^2 = S^2 * L(M^2)$$

focus on $\sigma^{bgd}_{hard}(M^2,\ldots)$

$L_{eff}(M^2, y)$ → the same for Signal and Bgds

$$L_{eff} \sim \frac{\hat{S}^2}{b^2} \left| N \int \frac{dQ_t^2}{Q_t^4} f_g(x_1, x_1', Q_t^2, \mu^2) f_g(x_2, x_2', Q_t^2, \mu^2) \right|^2$$

contain Sudakov factor T_g which exponentially suppresses infrared Q_t region → **pQCD**

$$< Q_t >_{SP} \simeq M/2 * \exp(-1/\bar{\alpha}_s) \approx 2 GeV \gg \Lambda_{QCD},$$

$$\bar{\alpha}_S \simeq (N_C/\pi) * \alpha_s(M) * C_\gamma$$

T_g + anom.dim. → *IR filter*

S^2 is the prob. that the rapidity gaps survive population by secondary hadrons → soft physics

between Scylla and Charybdis

(Uri's talk)

new CDF dijet results (Mike)

Helicity amplitudes $M^{\lambda_q,\lambda_q}_{\lambda_1,\lambda_2}$

$$g(\lambda_1, k_1) + g(\lambda_2, k_2) \rightarrow q(\lambda_q, p) + \bar{q}(\lambda_{\bar{q}}, \bar{p})$$

λi – helicities of 'active gluons'

S - Jz=0, LO, **B**- dominantly Jz=2

λ_q – (double) helicities of produced quarks

❋ convenient to consider *separately*
q-helicity conserving ampt (**HCA**) and q-helicity non-conserving ampt(**HNCA**)

- do not interfere, can be treated independently,

❋ for **Jz=0** $(\lambda_1 = \lambda_2)$ the Born HCA *vanishes*, $M^{\lambda_q,-\lambda_q}_{\lambda,\lambda} = 0$

Symmetry argumts (BKSO-94)

(usually, HCA is the *dominant* helicity configuration.)

❋ for large angles HNCA

$$M^{\lambda_q,\lambda_q}_{\lambda,\lambda} \sim \mathcal{O}\left(\frac{m_q}{\sqrt{s}}\right) M^{\lambda_q,-\lambda_q}_{\lambda,-\lambda}$$ (Jz=2, HCA)

in terms of the **MHV rules** the only nonzero amplitudes (S .Parke, T.Taylor (1986))

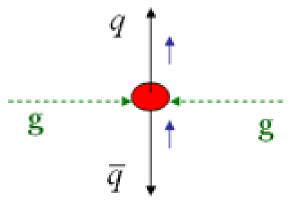
(+ - ; + -) J_z=2, **HCA**

(-+ ; -+ /+-) (massless limit)

an advantageous property of the $gg^{PP} \to q\bar{q}$ large angle amplitudes

- all **HNCA** (Jz=0, Jz=2, all orders in α_s) are suppressed by m_q / E_T
- all **HC** gg^{PP} ampts ((**Jz=0, Jz=2,** all orders) are prop. $\cos\theta$ → vanish at 90°

(z)



rotational invariance around q-direction (Jz=2, **PP**-case only)

$$60^{\circ} < \theta < 120^{\circ} \rightarrow |\eta_1 - \eta_2| < 1.1$$

(acceptance of CD and suppression of t-channel singularities in background processes)

- LO **HC**A vanishes in the Jz=0 case (*valid only for the Born amplitude*)

Jz=0 suppression is *removed* by the presence of an additional (*real/ virtual*) gluon (BKSO-94)

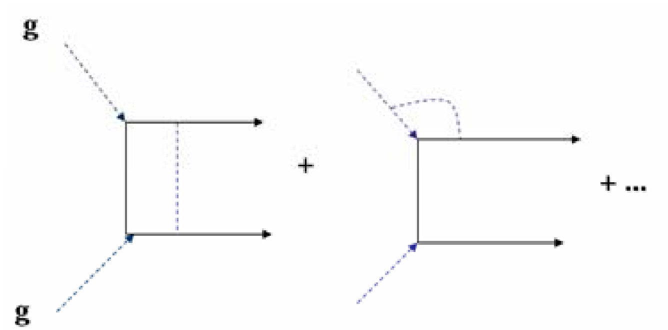
Classification of the $gg^{PP} \to q\bar{q}$ backgrounds

- $|J_z|=2$ **LO** production caused by **non-forward going** protons.

HC process, suppressed by $4p_{1t}^2 p_{2t}^2 / Q_t^4$. and by $\cos^2\theta$

$$\frac{B_{|J_z|=2}(gg^{PP} \to b\bar{b})}{S(gg^{PP} \to H \to b\bar{b})} \approx 0.02 * (\Delta M / 1GeV)$$

- **NNLO** $\mathcal{O}(\alpha_S^4)$ (cut non-reconstructible) **HC** quark box diagrams.



$$\frac{d\sigma^{NNLO}}{d\sigma_{\mathrm{Born}}}(gg^{PP} \to q\bar{q}, J_z = 0) \approx \alpha_s^2 / 32 * M^2 / m_q^2 * (C_F - N_C)^2 \sin^2\theta \cos^2\theta$$

- *dominant* contribution at *very* large Higgs masses M
- at M < 300 GeV still phenomenologically unimportant due to a combination of small factors
- appearance of the $(C_F - N_C)^2$ factor → consequence of supersymmetry

(SUSY theory with fermions in the adjoint representation (gluinos)) (L.Dixon)

$(C_F \to C_A)$

- **mass-suppressed Jz=0 contribution** $B/S_{SM} \sim \Delta M / M^5$

☹ **theoretically most challenging** (*uncomfortably large* higher-order effects)

- *naively* Born formula would give small background contribution
- however, various *higher-order* effects are essential :
  - running b-quark mass **Single Log** effects ($\overline{m}_b(M_H) < \overline{m}_b(m_b)$)
  - the so-called *non-Sudakov* Double Log effects , corrections of order

3F= $(8\alpha_S / \pi) * \ln^2(M / m_b) \geq 1$

(studied in FKM-97 for the case of $\gamma\gamma \to b\bar{b}$ at Jz=0)

Guidance based on the experience with QCD effects in $\gamma\gamma \to b\bar{b}$.

- DL effects can be reliably summed up(FKM-97 , M. Melles, Stirling, Khoze 99-00).
- Complete one-loop result is known (G. Jikia et al. 96-00)

-complete calculation of SL effects (drastically affects the result)

-**bad news** : ⁕ *violently oscillating* leading term in the **DL** non- Sudakov form-factor:

$$\text{Fq}= \left(1-\underbrace{(1+2N_C/C_F)}_{(\approx 2.5)}*F\right)^2+\ldots.$$

⁕ DL contribution exceeds the Born term; strong dependence on the NLLO, scale, running mass…. effects

⁕ No complete SL calculations currently available.

HNC contribution rapidly decreases with increasing M

Currently the best bet: :

$$\text{Fq} \approx \left[1 - \frac{m_b(M_H m_b)}{m_b(M_H^2)}(C_F+2N_c)\frac{\alpha_s(M_H m_b)}{\pi}\ln^2\left(\frac{c\cdot M_H}{m_b(M_H m_b)}\right)\right]^2 .$$

with $c\approx 1/2$.

Taken literally → factor of two larger than the 'naïve' Born term.

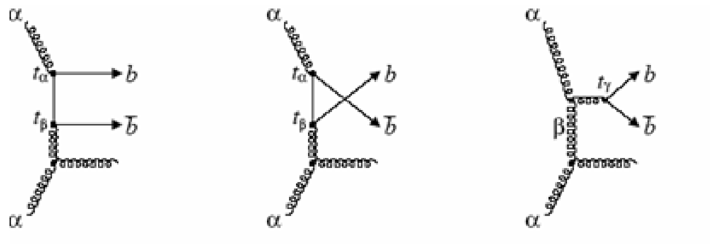
Cautiously : accuracy, not better than a factor of 4

A lot of further theoretical efforts is needed

A.Shuvaev et al.,
E.W.N. Glover et al.

NLO radiation accompanying hard $gg^{PP} \to q\bar{q}$ subprocess

Large-angle, hard-gluon radiation does not obey the selection rules



+ radiation off b-quarks (+ n soft gluons)

* potentially may be a *dominant* bgd :($\alpha_S / \pi >> (m_b / M)^2$) strongly exceeding the LO expectation.

$$B_{qqg} / S_{SM} \sim \alpha_S * \Delta M / M^3$$

* only gluons with $p_t \geq Q_t$ could be radiated, otherwise cancel. with screening gluon ($\lambda_g > d_t \sim 1/Q_t$).

* KRS-06 → complete LO analytical calculation of the HC , Jz=0

$|M_{gg \to q\bar{q}g}|^2$ in the massless limit, using MHV tecnique.

These results can/will be incorporated into MC programmes to investigate radiative bgd in the presence of realistic experimental cuts.

MHV-technique: an elegant way to write down the tree-level (and sometimes loop) amplitudes in a compact way, automatically accounting for the possible cancellations between different terms**,** caused by gauge invariance and symmetry properties (e.g. Parke & Taylor-1986).
Nowadays popular among (more) formal people E. Witten et al

$$g(p_1)+g(p_2)\rightarrow g(p_3)+q(p_3)+\bar{q}(p_4)$$

non-zero amplitudes: $\lambda_q = -\lambda_{\bar{q}}$

$$(++;--+),\ (++;-+-),\ (--;+-+),\ (--;++-)$$

MHV $ggg q\bar{q}$ scattering amplitudes (S. Parke, T.Taylor (1986))

$$\sum|\mathcal{M}|^2(J_z=0;\text{colour singlet}) = \frac{2}{9}\sum_{h=1}^{4}\Big|z(1,2,3,h)+z(2,1,3,h)+z(3,2,1,h)$$
$$+z(3,1,2,h)-\frac{1}{8}\left(z(1,3,2,h)+z(2,3,1,h)\right)\Big|^2$$

the only non-zero $J_z=0$ subamplitudes are

$$z(a,b,c;h) = ig_s^3\frac{\langle qc\rangle\langle\bar{q}c\rangle\langle Ic\rangle^2}{\langle\bar{q}q\rangle\langle qa\rangle\langle ab\rangle\langle bc\rangle\langle c\bar{q}\rangle}.$$

(I → $q(\bar{q})$ with the same helicity as the outgoing gluon c)

(angular brackets) $\langle ab\rangle = \langle p_a^-|p_b^+\rangle = \sqrt{|2p_a p_b|}e^{i\phi_{ab}}, \quad 2p_a p_b = s_{ab}$

How hard should be gluon radiation in order to overcome the Jz=0 selection rule ?

- for soft outgoing gluon **c** $\langle qc\rangle\langle\bar{q}c\rangle\langle Ic\rangle^2 \propto E_g^2$ → kills soft gluon log

and $$\frac{d\sigma(J_z=0)}{dE_g} \sim E_g^3$$ in marked contract to $$\frac{d\sigma_{\text{unpol}}}{dE_g} \sim \frac{1}{E_g}.$$

- collinear singularities corresponding to the gluon c- radiation in the $q(\bar{q})$ directions

(z(c,a,b;h), z(c,b,a;h)- amplitudes) is cancelled by the numerator. → no collinear logs

Bright consequence of Low theorem
(F. Low (1958)):

when M_{Born}= 0, non-classical (short-distance) effects start from the term $C_2 x_g^2$ in the expansion of radiative matrix element in powers of $x_g = E_g/E_b$

$$M_{\text{rad}} \sim \frac{1}{x_g}\sum_{n=0}^{\infty} C_n x_g^n,$$

(DKS-94, BKSO-94)

'Conventional' MC algorithms cannot be used

$$\frac{d\sigma_{\rm unpol}}{dE_g} \sim \frac{1}{E_g}$$ (*classical* infrared behaviour)

neglecting quark mass $$\frac{d\sigma(J_z=0)}{dE_g} \sim E_g^3$$

➔ the relative probability of the *Mercedes -like* qqg configuration for Jz=0 radiative background process becomes unusually large

✪ marked contrast to the Higgs-> bb (quasi-two-jet- like) events.

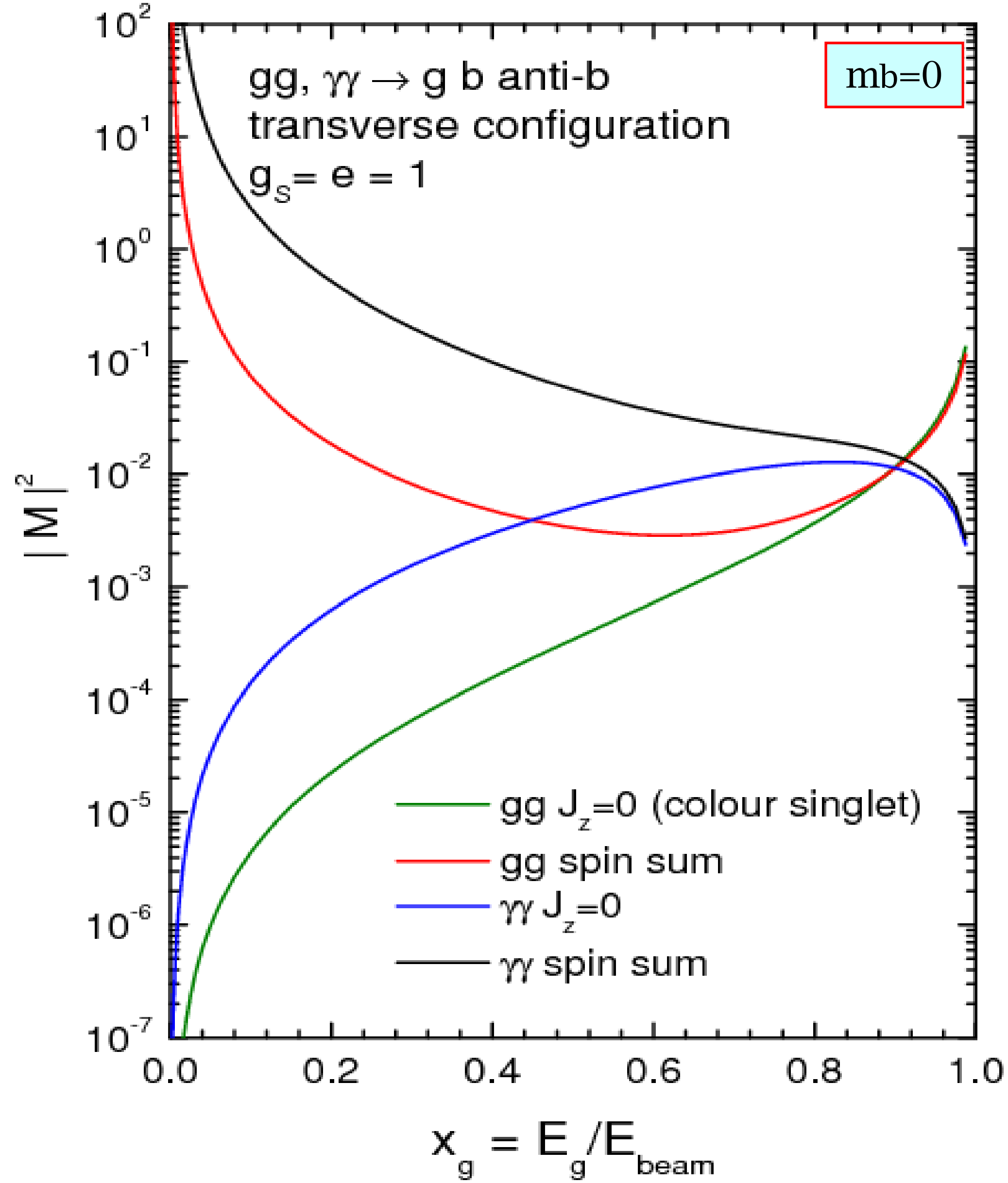
✪ charged multiplicity difference between the H->bb signal and the Mercedes like bbg – bgd:

for M ~120, ΔN ≈7, ΔN rises with increasing M.

- *the* clearly pronounced 3-jet events can be eliminated by the CD,
- can be useful for background calibration purposes.

Exceptions:
- radiation in the beam direction;
- radiation in the b- directions.

DKMOR-02, KMR-07



gg, γγ → g b anti-b
transverse configuration
g_S= e = 1
mb=0
gg J_z=0 (colour singlet)
gg spin sum
γγ J_z=0
γγ spin sum
$|M|^2$
$x_g = E_g/E_{beam}$

beam direction case

if a gluon jet is to go unobserved outside the CD or FD ($M \gg p_t > Q_t$)

→Violation of the equality : $M_{missing} \approx M_{bb}$ (limited by the ΔM_{bb})

contribution is smaller than the admixture of Jz=2. KRS-06

b-direction case (**HCA**)

$$\frac{B(gg^{PP} \to b\bar{b}g)}{S(gg^{PP} \to H \to b\bar{b})} \sim 0.2 *(\Delta R/0.5)^2$$

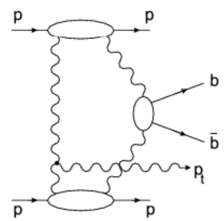
(ΔR -separation cone size)

Note : * soft radiation factorizes → strongly suppressed → *is not a problem,*
* NLLO *bbgg* bgd → numerically small

radiation from the screening gluon with pt~Qt :

HC (Jz=2) LO ampt. ~ $\cos\theta$ → *numerically* very small

* hard radiation - *power suppressed* $\sim (Q_t / p_t)^2$

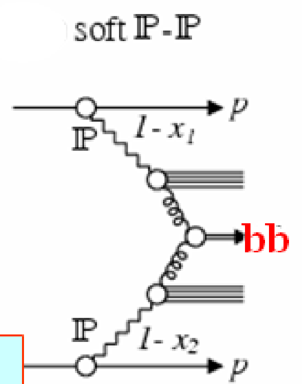


KMR-02

MHV results for gg(Jz=0)→ng amplitudes (dijet calibration, b-mistag)

Production by soft *Pomeron-Pomeron* collisions

main suppression : $M_{PP} = M_{missing}$ lies within



$M_{bb} \pm \Delta M_{bb}$ mass interval

suppr. factor $\frac{1}{2}(\Delta M_{bb}/M_{PP})^2 * g^2{}_P(1-\Delta M_{bb}/M_{PP}) \rightarrow B_{PP} < B(J_z = 2)$

(HI 2006 Fit B and http://www.hep.ucl.ac.uk/~watt/DDIS/

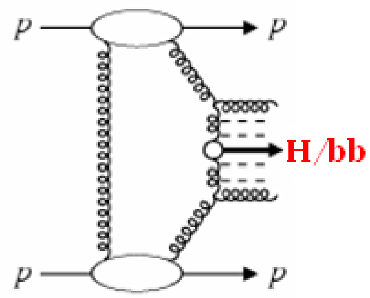
additional factor of ~100 suppression as compared to the 'old DPDFs'

Background due to *central inelastic* production

mass balance, again

subprocess $gg^{PP} \rightarrow Hgg$ is strongly *suppressed*

produces a *small tail* on the high side of the missing mass



Production by hard and soft *Pomeron-Pomeron* collisions

(KMR hep-ph/0702213)

Requirement: $M_{PP} = M_{missing}$ lies with mass interval $M_{bb} \pm \Delta M_{bb}$

Suppression: $\frac{1}{2}(\Delta M_{bb}/M_{PP})^2 * g^2{}_P(1-\Delta M_{bb}/M_{PP})$ (soft PP and qualitatively for hard PP)

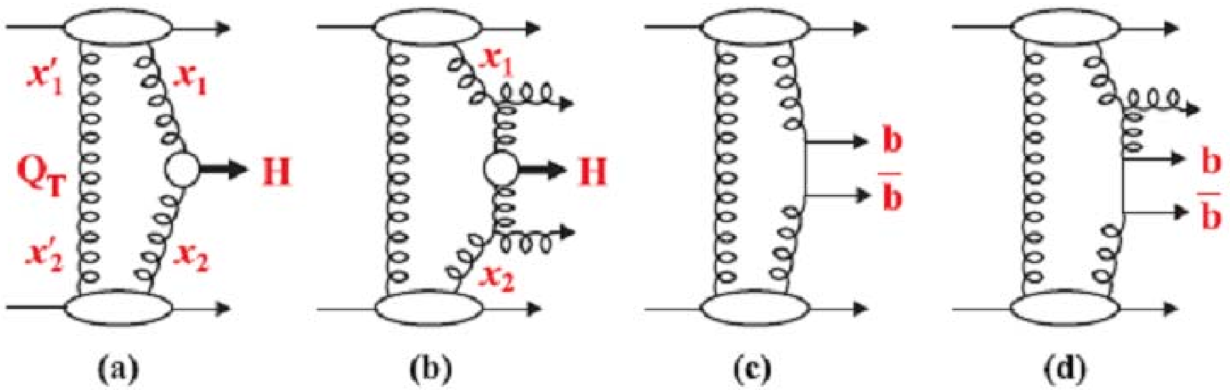


Figure 1: (a) Exclusive Higgs production by the fusion of two hard Pomerons; (b) Higgs production, via hard Pomerons, but accompanied by the emission of two undetected gluons; (c,d) background QCD $b\bar{b}$ production processes. For (b,c,d) we account for the full set of Feynman diagrams at this order and, moreover, for (b,d) allow for additional soft gluon emission.

New version of Pomwig is available

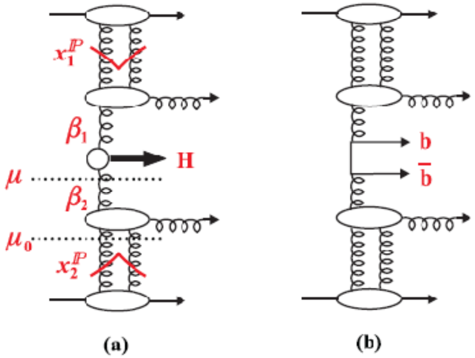


Figure 2: (a) Higgs production by the fusion of two soft Pomerons; (b) background $b\bar{b}$ production via soft Pomerons.

process	diagram	cross section	
$\sigma_{\rm excl}(H \to b\bar{b})$	Fig. 1(a)	150	exclusive signal
$\sigma(gHg)$	Fig. 1(b)	20	
$\sigma^{\rm QHNC}(b\bar{b}:{\rm LO})$	Fig. 1(c)	70	irreducible background
$\sigma^{\rm QHNC}(b\bar{b}g)$	Fig. 1(d)	5.2	λ not conserved
$\sigma^{\rm QHC}(b\bar{b}g)$	Fig. 1(d)	0.6	negligible; λ conserved
$\sigma^{\rm DPE}(gHg)$	Fig. 2(a)	0.14	negligible
$\sigma^{\rm DPE}(gb\bar{b}g)$	Fig. 2(b)	9	small

Table 1: The cross sections $d\sigma/dy|_{y=0}$ (in units of 10^{-3} fb) of the hard Pomeron processes shown in Fig. 1 and the soft Pomeron processes of Fig. 2. In each case the $H \to b\bar{b}$ branching ratio has been included and a polar-angle cut $60° < \theta(b) < 120°$ in the Higgs rest frame has been applied to the b jet, that is the jet rapidity separation $|\eta_1 - \eta_2| < 1.1$. We have taken $M_H = 120$ GeV, and assumed that the mass resolutions of the central detector and roman pots are such that they correspond to mass windows $\Delta M_{\rm dijet}/M_{b\bar{b}} = 20\%$ and $\Delta M_{\rm missing} = 4$ GeV, respectively. λ is the helicity along the b quark line. For the processes of Fig. 1(b,d), we allow for the emission of any number of gluons with transverse momentum $k_T < k_{T,\max} = 5$ GeV.

Approximate formula for the $b\bar{b}$ background

$$\sigma_{\mathrm{B}} \approx 2\,\mathrm{fb}\left[0.92\frac{\Delta M}{(4\ \mathrm{GeV})}\left(\frac{120}{M}\right)^{6}+\frac{1}{2}\frac{\Delta M}{(4\ \mathrm{GeV})}\left(\frac{120}{M}\right)^{8}\right]$$

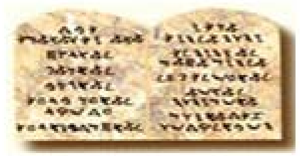
main uncertn. at low masses

ΔM- mass window over which we collect the signal

- ✶ b-jet angular cut : ($60^{\circ} < \theta < 120^{\circ} \rightarrow |\eta_1 - \eta_2| < 1.1$)
- ✵ both S and B should be multiplied by the overall 'efficiency' factor ε (combined effects of triggers, acceptances, exp. cuts, tagging efficienc., ….), ε ~4.2 % (120 GeV)
- ✶ g/b- misident. prob. P(g/b)=1.3% (ATLAS)

Four major bgd sources ~ (1/4 +1/4 + $(1.3)^2/4$ + 1/2) at M≈120 GeV, ΔM= 4GeV

Conclusion

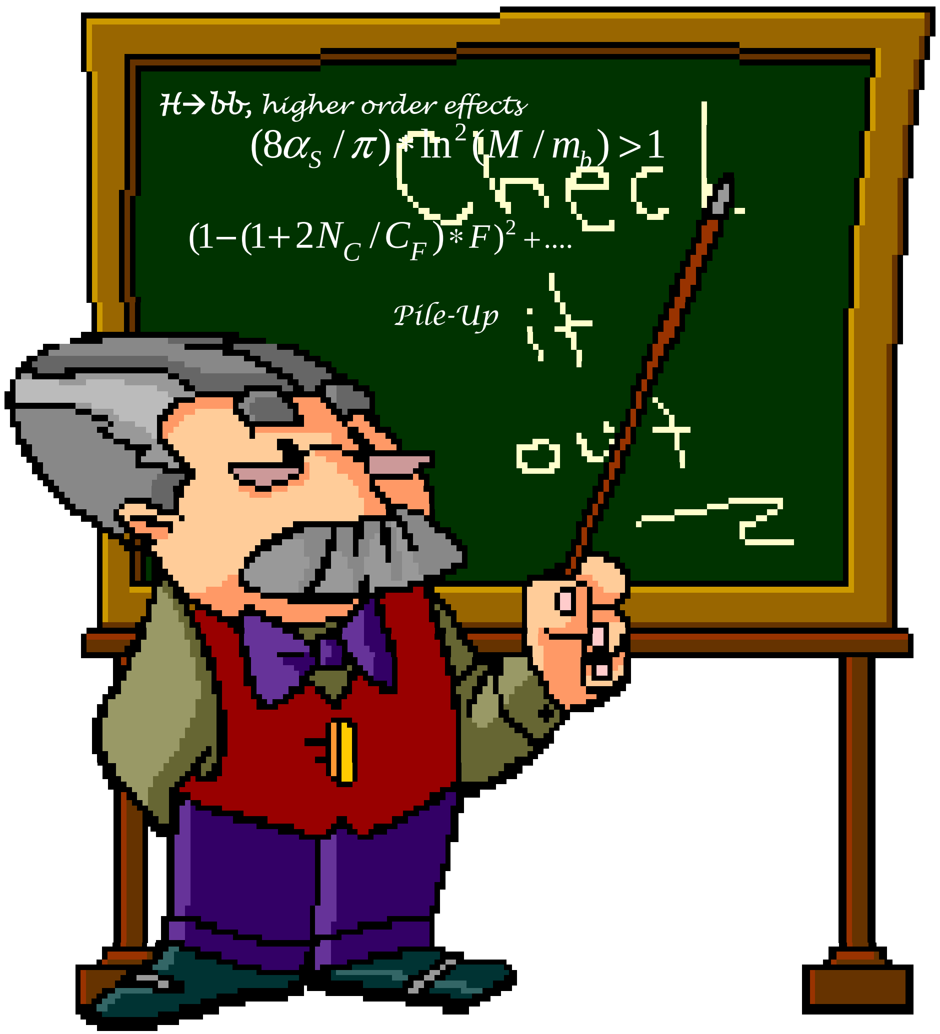


God Loves Diffractive Higgs

- Strongly suppressed and controllable QCD backgrounds in the forward proton mode provide a potential for direct determination of the Hbb Yukawa coupling, for probing Higgs CP properties and for measuring its mass and width.
- In some **BSM** scenarios $pp \to p + (H \to bb) + p$ may become a *discovery channel* at the LHC.
- Further bgd reduction may be achieved by experimental improvements, better accounting for the kinematical constraints, correlations…..
- The complete background calculation is still in progress (*unusually & uncomfortably* large high-order QCD effects, Pile-Up at high lumi)

Further theoretical & MC and experimental studies are needed

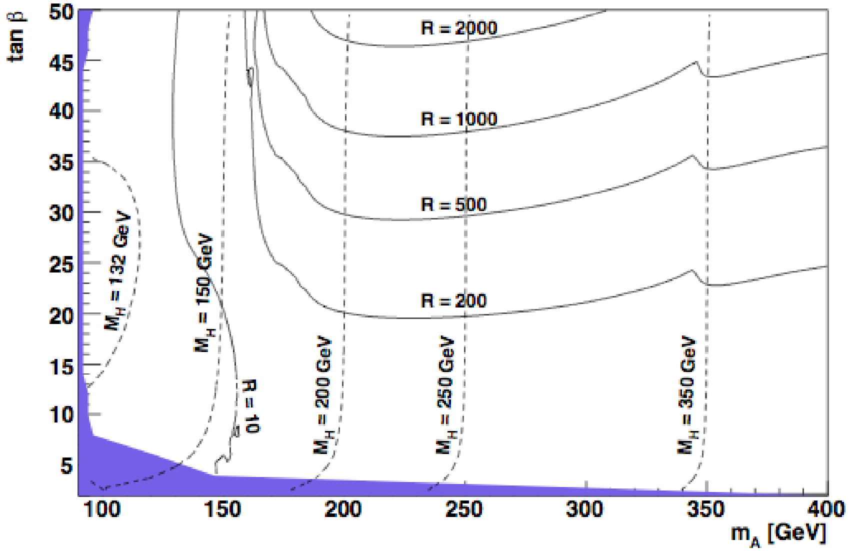
FP420 still needs theorists after all



Heinemeyer, Khoze, Ryskin, Stirling, Tasevsky, Weiglein-2007

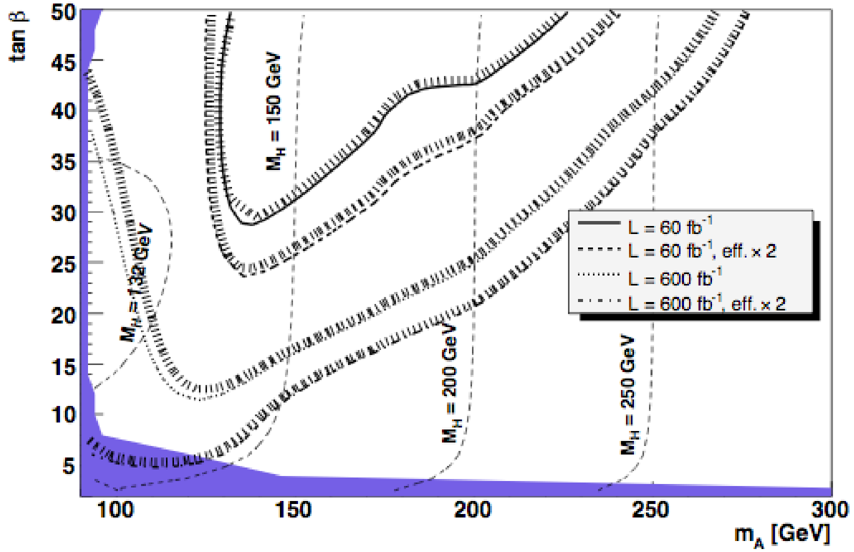
m_H^{max} scenario

$\mu = -500$ GeV



Ratio of MSSM (H production) to SM (h) production.

(Marek's talk)



Assumes that the overlap background can be neglected (ok at low lumi, and may also be possible at high lumi).

(Andy, Marek's talks)